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13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official department of ASOSR position, policy or decision.

14. ABSTRACT This AASERT was linked to the parent AFOSR project AFOSR F49620-96-1-0393, to develop fundamental knowledge on shock response and geo- and cementitious materials, through a coordinated, multidisciplinary research effort. The AASERT research focuses on systematic experimental investigation, paralleled with physically-based micromechanical modeling and computational simulation of the shock response of advanced cementitious materials. By collaborating with Eglin and Tyndall Air Force Base, fundamental contributions were made toward a solution to this class of problems. A series of quasi-static and dynamic experiments using the existing state-of-the-art material testing and novel recovery Hopkinson facilities at UCSD's CEAM. Damage initiation and evolution was systematically documented, using material characterization techniques. Based on these observations, physically-based models which capture the essential features of the process of damage evolution were developed for computational simulation. These models will be cast into a framework suitable for implementation into large-scale computer programs and will be checked against independent experiments.
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Experimental Investigation and Computational Modeling of Shock Response of Cementitious Materials

FINAL TECHNICAL REPORT

01 June 97 - 31 December 00

**GRANT NO. AFOSR F49620-97-1-0421
(AASERT'97)**

to

University of California, San Diego

by

Air Force Office of Scientific Research

Principal Investigator: Dr. S. Nemat-Nasser

**Center of Excellence for Advanced Materials
Department of Mechanical and Aerospace Engineering
University of California, San Diego
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Submitted August 2001

I. Summary

The research done under AASERT has been varied and successful. The research effort focused on developing a high strain-rate model for concrete under compression. In the course of this research, new experimental and analytical techniques have been developed. Mr. Jacob Rome has traveled to both Eglin Air Force Base (twice) and Tyndall Air Force Base to meet with the scientists and engineers working there. While participating in collaborative workshops, making or attending presentations, and touring the laboratories in Florida, Mr. Rome was better able to understand the nature of the problems and the challenges in solving them.

The scientists and engineers at Tyndall and Eglin Air Force Bases provided us with concrete, mortar and limestone that we could machine as necessary and use for a range of experiments. At UCSD, new experimental techniques have been developed, as a direct result of this research, for high strain-rate testing of concrete and mortar in triaxial compression. We have used these new techniques and the wide range of other experimental set-ups at UCSD to conduct a broad range of experiments. Using our unique facilities, we have been able to test mortar and limestone samples at high strain rates and recover these samples for damage assessment. Low strain-rate testing, ultrasonic experiments and scanning electron microscopy (SEM) techniques have been used to characterize the material, assess the damage and measure the properties of tested and untested samples. These novel techniques have allowed us to better model the response of concrete.

A micromechanics model to predict the elastic modulus of concrete has been developed. This micromechanics model has been implemented numerically using the commercial software *Mathematica*. This elastic model forms the basis of the overall material model used to predict the response of the concrete at high and low strain-rates under uniaxial and triaxial compression. The overall material model is implemented in *Mathematica* and can be modified for use in a finite element program (FEM).

The past year, we have focused our research on refining the model for the high strain-rate response of concrete. Experiments, which have been designed, developed and verified in prior years, have been used to more systematically examine the response of concrete and its constituent materials. The material model, which incorporates damage parameters, is developed using principles of micromechanics, material characterization and experimental results. The model is implemented numerically using the commercial software *Mathematica*. Experiments have included tests on both concrete and its

constituents (mortar and the limestone aggregate) at a range of strain rates, using uniaxial and triaxial compression.

Research Personnel Associated with this Project

Dr. Sia Nemat-Nasser (PI)

Mr. Jacob Rome (AASERT Graduate Student Researcher)

Mr. Jon Isaacs - Sr. Development Engineer

Degrees Attained: None as of December 2000. It is anticipated that Jacob Rome will receive his Ph.D by September 30, 2001.

II. Status of Research Effort

II.1. High Strain-Rate Triaxial Tests

A 3/4" Hopkinson Bar has been modified for the purpose of conducting triaxial tests at high strain rates on mortar. A photograph and a schematic of the test equipment is shown below in Figure 1. With this set-up, we are able to dynamically load a sample in both the radial and axial directions. The radial stress is measured along with the axial stress and strain.

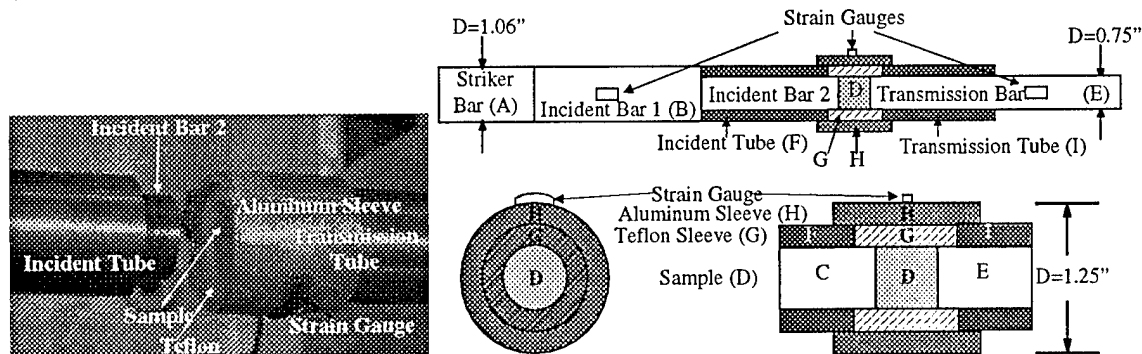


Figure 1: Photograph and schematic of confining Hopkinson Bar

In the past year, we have conducted many experiments on mortar using this set-up. The tests have been designed to directly examine the effects of strain rate and the radial stress on the axial stress-strain response. Triaxial tests on concrete will be done using a different set-up. The radial confining pressure dramatically affects the response of the mortar. The confined and unconfined response of the mortar is contrasted on the left side of Figure 2. This figure also shows how the response is affected by the magnitude of the

confinement. The effect of strain rate on the response of confined mortar is shown on the right side of Figure 2.

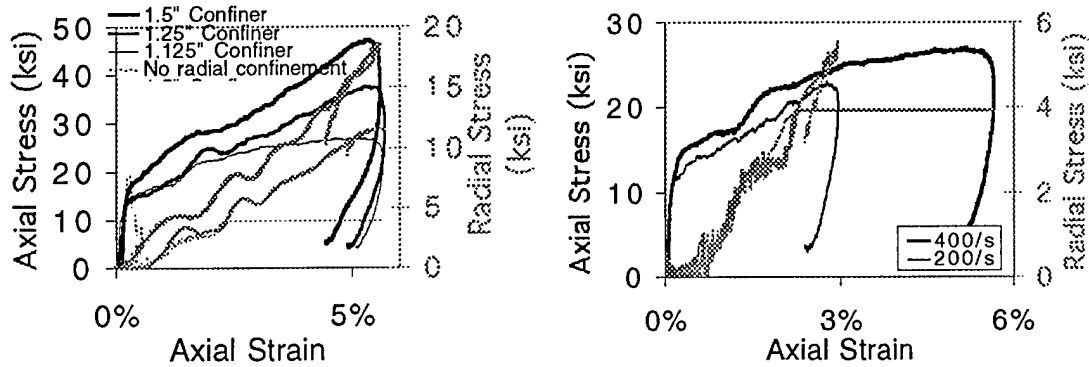


Figure 2: High strain-rate tests on mortar. Left: comparison of triaxial response of mortar at different levels of confinement and comparison to uniaxial response (at 400/s). Right: Triaxial response of mortar at different strain rates.

II.2. Low-strain rate tests

Tests on concrete, mortar and limestone aggregate have been done at low strain rates using a 20kips Instron machine. These tests were done on samples with a diameter of about two inches. On some tests on concrete, the samples were loaded beyond the elastic limit. Reloading these samples demonstrates that the sample has been permanently damaged during the test. After the sample has been loaded into the inelastic region, the modulus is much lower. On the left side of Figure 3, the elastic response and modulus is shown for two samples; the elastic response of sample 2 is shown after the it was tested to higher strains, shown on the right side of Figure 3. Together, these experiments demonstrate that much of the non-linear response of concrete is due to the reduction of the elastic modulus.

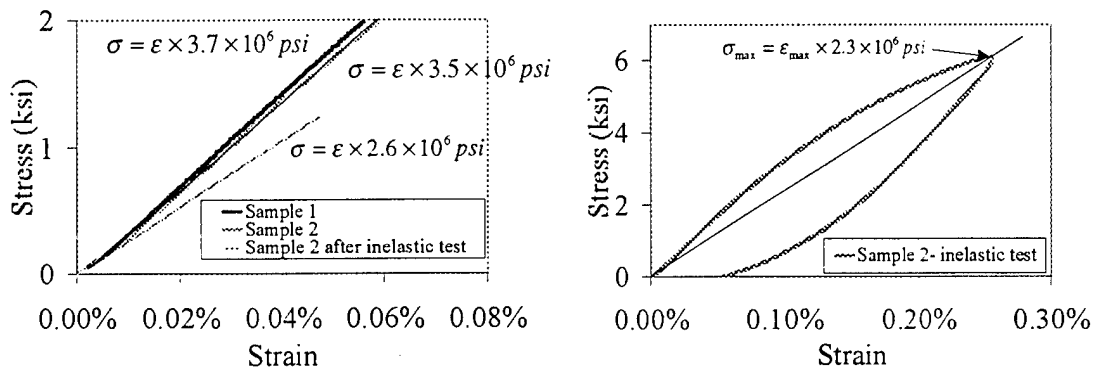


Figure 3: Response of concrete during low strain rate tests

II.3. Physically -based modeling

The model we are developing is sketched in Figure 4. The model assumes that a limestone aggregate is embedded in the mortar, and the mortar is embedded in a material which has the modulus of the overall structure. One or more cracks are embedded in the mortar or the limestone aggregate. The interface between the limestone aggregate and the mortar is treated like a crack. Currently, the model assumes that cracks exist at the interface; the model has been designed with sufficient flexibility that it could treat the interface differently. This may involve modeling the interface as a crack with resistance, or using another approach.

The modulus of the overall structure is calculated based on the stated assumptions and principles of micromechanics. Given the loading conditions, the response is found, and the cracks-- in the mortar, in the limestone aggregate, and at the interface-- grow using a rate-based criterion. After an increment of loading and crack growth, the new modulus is calculated. Therefore, this model takes into account the interaction between the limestone and the cracks, and also the strain-rate effects. Of course, the crack lengths are tracked and this is the damage parameter for the material. This model has been programmed using the commercial software package Mathematica.

A sample parametric study to calculate the modulus based on a given damage state is shown in Figure 4. The Young's modulus of the overall material is estimated based upon the crack-density at the interface, and the volume percentage of limestone aggregate. In this example, the shear modulus of the limestone inclusion is 5 times the shear modulus of the mortar. The ITZ crack density is the damage parameter; as the damage increases, the modulus decreases.

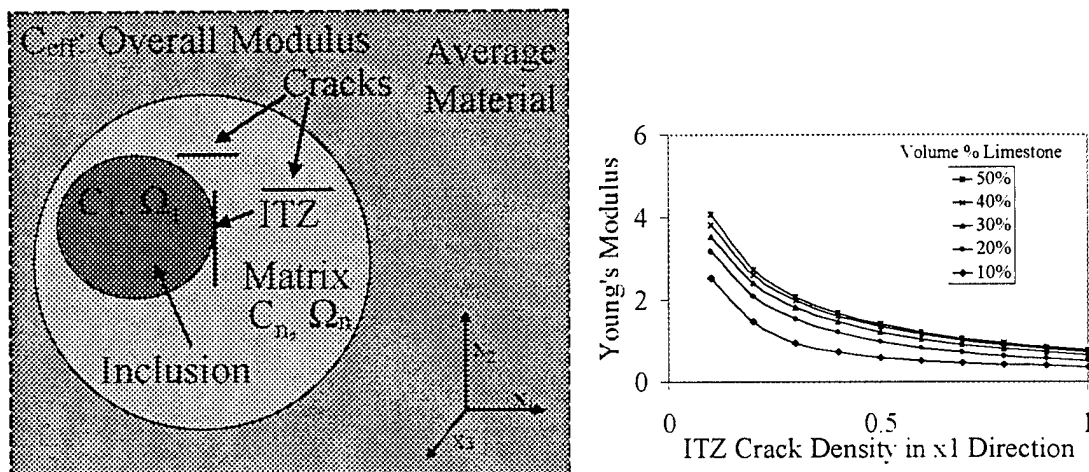


Figure 4: Geometry used to calculate concrete modulus and parametric examples using model

III. Summary and Description of Future Work

This project is in its final stages. A few experiments, triaxial and uniaxial high strain rate tests on concrete, will be done to refine the physically-based model for concrete response. The model, in its entirety, will be implemented in Mathematica to predict the response of concrete under triaxial compression at high and low strain-rates. This work will be completed in the next few months, as the graduate student working on this project plans to complete his dissertation in that time frame.

IV. Publications

Published work

Nemat-Nasser, S., J. Isaacs, J. Rome, "Triaxial Hopkinson Techniques," *ASM Handbook, Volume 8: Mechanical Testing and Evaluation*, pp. 516-518, 2000.

Works in Progress

- Rome, J., and S. Nemat-Nasser, "New Experimental Techniques of High-Strain Rate Testing of Concrete"

Abstract:

We have adapted old techniques and developed new techniques to study the dynamic response of concrete. Concrete was tested at high strain rates using the Split Pressure Hopkinson Bar (SPHB), also known as the Kolsky Bar. The samples were tested in both uniaxial and biaxial compression. Further, on many uniaxial tests high speed photography was employed to observe the loading and unloading process in the samples. Microscopy and other visual methods were employed to observe the concrete after biaxial tests.

- Rome, J. and S. Nemat-Nasser, "A Micromechanics Model to Find the Elastic Modulus of Concrete"

Abstract:

A micromechanics model is developed to estimate the modulus of concrete. Eshelby's inclusion theorem is used as the basis for the model. The concrete is treated as a two-phase material, the mortar (aggregate) and limestone (inclusion). The interfacial transition zone (ITZ) between the mortar and limestone is treated as a crack. Cracks may also be included in the mortar and limestone phases. The additional strain caused by each embedded crack is calculated based upon the average stress in the mortar or limestone. The additional strain caused by the ITZ is calculated based upon a weighted average of the stress. The influences of the cracks, including the ITZ, are accounted for in a self-consistent manner, and the model as a whole is self-consistent. Results are presented for a sample case. The results show that from the measured modulus of the mortar and

limestone, the modulus of the concrete can be predicted. This model builds on the work of Eshelby, Mori-Tanaka, Nemat-Nasser and others. It focuses on the primary features of the concrete—the mortar, aggregate, and cracks—so the modulus can be found numerically. The model can be used for any material with similar features; in fact, if some features are removed, the model can be reduced to different well-known models such as the self-consistent or double inclusion model. This paper explains the model, compares it to experimental results and presents some parametric studies.

- Rome, J., S. Nemat-Nasser and J.B. Isaacs, "A New Technique for True Dynamic Triaxial Testing with a Hopkinson Bar"

Abstract:

A new technique is described for triaxial compression testing at high strain rates. A Hopkinson bar is modified to simultaneously load a sample in both the axial and radial directions. This is accomplished by adding a second incident bar, an incident tube and a transmission tube. The sample being tested is placed inside a Teflon sleeve, which is in turn inside an aluminum sleeve. The Teflon sleeve is loaded during the test, which produces a large radial stress on the sample. The radial stress can be calculated from the measurement of the hoop strain on the aluminum sleeve. Mortar samples have been tested under a range of confining stresses and strain rates, and the results are presented.

V. Workshops and Conferences

Jacob Rome attended the "Invitational Workshop on Thermomechanics of High Speed Penetration" Graduate Engineering Research Center, University of Florida, Shalimar, Florida, August 17-18, 2000

"A Micromechanics Model to Predict the Elastic Modulus of Concrete" Lecture presented by Jacob Rome, Symposium on Current Development In Micromechanics Of Random Heterogeneous Materials And Bodies, 2001 Mechanics and Materials Conference, San Diego, California, June 27-29, 2001

"A New Triaxial Hopkinson Bar Technique: Development and Results" Lecture presented by Jacob Rome, Symposium on Experimental Techniques, 2001 Mechanics and Materials Conference San Diego, California, June 27-29, 2001

"Concrete Deformation under High Strain Rates: Experimental Methods and Results." Lecture presented by Jacob Rome, ASME International Mechanical Engineering Congress & Exposition, Anaheim, California, November 1998.

"Dynamic Response, Residual Strength and High Strain Rate Behavior of Concrete." Lecture presented by Jacob Rome, Shock Physics Preview Meeting, 12th ASCE Engineering Mechanics Conference, San Diego, California, May 1998.